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A PRELIMINARY INVESTIGATION OF THE ELECTRICAL STRUCTURE OF THUNDERSTORMS

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SUMMARY

The electrical charge structure of thunderstorms was studied by the use of continuously synchronized records of the electrical-potential gradient at the surface of the earth under the influence of active storms. The potential-gradient records were obtained from eight recording generating voltmeters that indicate the potential gradient with a time-resolving power of 1 second.

The sudden changes in the potential gradient due to lightning strokes were used to calculate the sign, the magnitude, and the position of the charge change associated with individual strokes. An analysis of a large number of lightning strokes indicated charge magnitudes from 10 to 190 coulombs. These strokes include transfers of negative electricity to the ground in the case of cloud-ground strokes and discharges that dissipate dipoles within the cloud. Calculations of the position of the dipole elements indicate that a typical thunderstorm has a negative charge center about 1.5 miles above the base of the cloud and near or within the region of maximum vertical convection. This negative charge center is associated with a positive charge center that, in the initial stage, is always above the negative charge center with a charge separation of approximately 0.5 mile. The upper positive charge center is frequently shifted away from the vertical position and toward the direction of motion of the storm. The existence of this charge configuration is confirmed by the continuous pattern of gradients as indicated on the several recorders.

The earliest discharges that occurred in a storm were found to consist of strokes which discharged nearly vertical dipoles. As the storm developed, the separation between the elements of the dipole increased and, when the activity was sufficiently intense, strokes occurred between the lower negative charge center and the ground. As the storm progressed, the positive charge center sometimes spread to the outer and the lower edges of the cloud and thus gave rise to

inclined and, in some cases, nearly horizontal discharges. The processes of charge generation appeared to be directly associated with the existence of precipitation forms, and no considerable amount of charge separation was found in clouds before the cumulo-nimbus phase was exhibited. Both positive and negative charge centers were found to be above the calculated position of the zero isotherm.

INTRODUCTION

In reference 1 is described a recording generating voltmeter that gives a continous record of the electrical-potential gradient at the surface of the earth due to thunderstorms. From six to eight of these generating voltmeters have been used in such a way as to give a continuous synchronized record of the potential gradient at the surface of the earth over an area of about 80 square miles during thunderstorm activity.

Preliminary reports of these investigations (references 1, 2, and 3) have shown that records thus obtained for a number of stations during the activity of thunderstorms provide a reliable method of determining (1) the signs, the magnitudes, and the positions of charges involved in lightning strokes by observing the potential-gradient changes produced by the lightning strokes at each of several stations in the vicinity of the storm, and (2) the approximate gross charge structure of a storm by observing the sign and the magnitude of the potential gradients at several stations.

This report gives results of charge distribution in thunderstorms obtained through the use of eight of an improved type of recording generating voltmeter during the summer of 1939. The potential-gradient data have been correlated for the first time with continuous motion-picture photographs (at 10-sec intervals) of the cloud during the period of influence over the instrument field. In addition, careful visual observations relative to cloud location, form of cloud, and type and position of visible discharges were made from the observation tower at the Albuquerque Airport.

The writers wish to acknowledge the generous cooperation of the United States Weather Bureau in many phases of this work. The Weather Bureau made available at all times the observation facilities of the Albuquerque station. Mr. Erle Hardy and Mr. C. F. Van Thullenar of the District

Weather Bureau extended valuable personal assistance in consultation on meteorological problems. Valuable assistance in obtaining field data was rendered by Mr. Gerald Bowen, Mr. David Lyon, and Miss Elizabeth Roorbach, students at the University of New Mexico.

THEORY OF METHOD

The surface of the earth is represented as an infinite conducting plane in figure 1. A charge of electricity at some height H above the surface will, if it is concentrated or spherically symmetrical, produce a normal gradient at any point P a distance R from O such that

$$E = \frac{2\ QH}{(H^2 + R^2)^{3/2}}$$

in electrostatic units. This result follows directly from classical image considerations of electrostatics. If Q is in coulombs and H and R are in miles, then E in volts per centimeter will be

$$\frac{70\ QH}{(H^2 + R^2)^{3/2}}$$

The surface-gradient pattern is symmetrical about the vertical axis. It is of interest to recall that the value of the potential gradient at any point on the surface is equal to $4\pi\sigma$, where σ is the surface density of the charge induced on the surface of the earth, measured in electrostatic units. The summation of the surface charge over the entire area influenced by the cloud charge will, of course, be equal and opposite to the net charge Q.

If more than one concentrated charge exists above the plane, the resultant potential gradient at a point on the surface may be determined by taking an algebraic sum of the gradients for the separate charges as determined by the foregoing relation. The solid curve in figure 2 shows values of the potential gradient at various distances from the vertical axis of a 100-coulomb charge 2 miles high. The dashed curve gives values for a 100-coulomb charge 4 miles high. If these two charges of opposite sign were to exist simultaneously as a dipole, the resultant potential gradient at the various points on the surface would be indicated by taking the difference in the corresponding ordinates of these two curves.

Figure 3 shows the potential-gradient pattern for two dipoles, one of which is vertical and the other inclined. The vertical dipole consists of two opposite charges of 100-coulombs magnitude, one 2 miles high and the other 3 miles high. The inclined dipole has the upper charge displaced 1 mile to the right of the origin. It should be noted that the potential-gradient pattern due to the vertical dipole, represented by the solid curve in figure 3, is symmetrical about the vertical-dipole axis. The potential-gradient pattern due to the inclined dipole is symmetrical only with respect to a plane through the dipole axis perpendicular to the surface of the earth. The dotted curve in figure 3 shows the variation of the surface gradient along the intersection of this plane and the surface.

If only one concentrated charge exists above the surface, it can be completely described by four coordinates: three space coordinates and a charge magnitude. Experimentally, the magnitude, the position, and the sign of the charge can then be completely determined by four independent measurements of the gradient at the surface of the earth. Hence, four recorders are sufficient for the determination of a single charge. In general, the quantitative determination of n concentrated charges requires $4n$ coordinates or $4n$ recorders. One important special case is worthy of mention. If the structure is a simple dipole, it may be described by seven coordinates instead of eight because the magnitudes of the two charges in the dipole are equal.

It is at once evident that a complete quantitative description of a single thunderstorm at any one instant would require a prohibitively large number of recorders and that the analysis of the data would be very difficult, if possible at all. The key to the successful quantitative application of the technique here described is the lightning stroke. In general, the lightning-stroke discharges limited portions of the thunderstorm consisting of one or more charged regions that may be treated as concentrated charges if the recorders are widely distributed over the surface of the earth underneath or near the storm. If the potential gradients at a number of recorders are measured immediately before and immediately after a stroke, the difference in the respective gradients before and after the stroke is the gradient pattern of the charge structure involved in the stroke. This pattern is frequently simple enough for analysis with eight recorders because many strokes carry a charge of one sign from cloud to ground or discharge a single dipole within the cloud. In complicated repeated strokes or in sequences of strokes, which are frequently observed visually and photographically, eight recorders do not supply sufficient data for quantitative analysis. An extension of the technique for analyzing these more complicated strokes by use of eight recorders with the high time-resolving powers is described under Discussion of Results.

The magnitude and the sign of the gradients at eight recorders, observed at any instant when no lightning stroke occurs, cannot be used for quantitative analysis of the storm. In spite of this fact, a study of the gradient trends as a storm grows or diminishes, or approaches and passes across the instrument field, gives valuable qualitative information about the gross storm structure.

APPARATUS

The instruments used during the summer of 1939 are very similar in construction and operation to those described in reference 1 except for the following modification: The sensitivity has been increased to the extent that the instruments are capable of indicating values of the same order of magnitude as fair-weather potential gradients at the surface of the earth. This increase in sensitivity was accomplished through the use of a more sensitive electrometer. Better temperature control and the elimination of mechanical vibrations were obtained by using two boxes for each installation. One of these boxes contained the driving motor, the rotating sector, and the lamp; the second box connected to it by means of a short rubber tube (3 in. in diam.) housed the electrometer, the recording mechanism, and the electrometer batteries.

A schematic drawing of the improved electrometer is shown in figure 4. A quartz torsion-type element similar to that of the earlier model was used with a plate system consisting of quadrants of a short cylinder of brass 1.25

inches long. A thin piece of brass foil was soldered to each quadrant in such a way that it could be propped away from the thicker metal of the quadrant and thus provide a simple means of adjusting the deflection characteristics of the instrument. The deflecting element shown in the figure consists of a thick quartz fiber (25 microns in diameter) that was cemented across the center of a torsion fiber from 5 to 8 microns in diameter and about 1 inch long. This deflecting element has a rake-like structure of quartz at one end (see fig. 4) with five short fibers extending parallel to the torsion fiber. These short fibers provide multiple indicators that have the effect of lengthening the scale. The other end carries a short heavy fiber mounted parallel to the torsion fiber for mechanical and electrical balancing.

The quadrant plates of the electrometer are maintained, in opposite pairs, 45 volts above and below ground, respectively; the element is directly connected to the commutator brush that makes contact with the rotating sector. Light from the illuminated indicators passes through a narrow slit in the plate system to the lens that forms images of the indicators on an 0.001-inch recording slit.

This arrangement of plates and deflecting element is advantageous in that it is relatively easy to adjust the instrument so that the voltage sensitivity is much greater in the lower ranges. Also, extreme deflections cannot cause the deflecting element to stick to any of the stationary parts.

The weatherproof boxes housing the instruments were mounted in the ground in such a way that the top of the box would be effectively flush with the nearly level ground. Considerable care in selecting sites was taken to avoid close proximity to extended ground objects such as buildings, trees, and power or telephone lines. In no case did a ground object extend more than 5° above the horizontal as viewed from the instrument positions. Each instrument was connected to a power line through a rubber-covered wire placed just under the ground. Figure 5 is a map giving the location of each instrument by number and a scale of miles, with the observation tower on the administration building of the Albuquerque Airport taken as an origin. The approximate outline of the city of Albuquerque is shown as a shaded portion of this map.

The region near Albuquerque has a relatively smooth terrain with a gradual slope from the east and from the west toward the Rio Grande. The extreme eastern border of this region is bounded by mountains that rise abruptly to a mean height of approximately 4500 feet above the land to the west of them. This ridge, consisting of the Sandia Mountains at the north end and the Manzano Mountains at the south end, extends in a north-south direction along a line approximately 12 miles east of the airport station.

DISCUSSION OF METHOD

Observations taken in the manner indicated provide the following lines of attack on problems of thunderstorm structure.

A. Visual and photographic observations from two different stations make possible the location of the clouds in space, the location of the region of most rapid vertical growth, and the rate of progress of the storm.

B. Visual observation of the position of lightning strokes, frequency of occurrence of visible strokes, and position and extent of rain sheets may be used to supplement the data on clouds or, in part, to replace the cloud observations when the sky is overcast.

C. Data from the potential-gradient recorders can be used in two ways. First, information on the sign and the magnitude of the simultaneous gradients at several stations gives a gross qualitative picture of a nearby storm and, second, an analysis of the sudden changes in the potential gradients accompanying lightning strokes gives a picture more limited in scope but more detailed and quantitative.

If reasonable care is taken in obtaining and using the data, the validity of the first two methods of attack on thunderstorm structure cannot be seriously questioned. Several important questions may arise, however, as to the meaning and the use of the data obtained by the gradient recorders: (1) Do the recorders measure gradients at the surface in a reliable manner? (2) Are the surface gradients seriously affected by space charges between the cloud and the ground? (3) To what extent are the assumptions made in calculations of charge magnitude and position valid, under actual thunderstorm conditions?

These questions may be answered in the following way:

(1) A number of tests have been made in laboratory and field to check the validity of the measurements and the reliability of the instruments. The instruments were visited on an average of once a day and were calibrated in place soon before or just after each storm. Calibrations were made by placing a plate above the top of the recorder and parallel to the recorder and maintaining it at known potentials with respect to the box. The recorder gave the same response within the tolerated limits of accuracy for the same calculated potential gradient regardless of the plate separation as long as the edge effects of the condenser formed by the plate and the box were not significant. Furthermore, the speed of response to rapid changes in the potential gradient was adequate to indicate reliably the changes in potential gradient due to individual strokes separated in time by 1 second or more; that is, the total change in gradient during a stroke was accurately measured but the changes in gradient due to the separate elements of a repeated lightning stroke were not recorded. (On several occasions the electrometer indicator underwent such rapid fluctuation that good photographic traces were not made.)

(2) It is well known that, when potential gradients which exist under thunderstorms become sufficiently great, many ground objects with large curvature, such as twigs and needles of trees and bushes, wires, etc., produce corona discharges. If these corona discharges give rise to an appreciable space-charge sheath above the surface of the ground, the surface gradient will be materially affected. While an active thunderstorm is passing over an instrument, lightning discharges passing into or through the region between cloud and ground may introduce charges in this space and thereby mask the charge structure above it.

The possible effect of these space charges on the results must be estimated by careful examination of the experimental data. In the case of sudden changes in the potential gradient accompanying lightning strokes, the answer is fairly clear. Changes in potential gradient due to lightning strokes can frequently be observed several miles (up to 15 miles by the method described in this paper) from the active region of the storm in cases where the resultant potential gradient due to the storm as a whole is less than 10 volts per centimeter and, in some cases, as low as the normal gradient of the earth.

Analysis of the charge structure producing these changes gives the same approximate heights of the charges above the surface and the same order of magnitude of the charge as an analysis of potential-gradient changes in the case of storms close to or over the instruments. It is safe to assume, therefore, that, in conclusions based on sudden changes in the gradient, the effect of space charges between cloud and earth do not cause errors large enough to affect the order of magnitude of height or the quantity of charge as calculated from the measurements. In nearby storms a larger percentage of small charges are measured, but this result is to be expected because only the largest discharges would measureably affect the distant instruments.

In deductions based on the magnitude of the potential gradient rather than on the rapid changes in the gradient, effects of space charges may be more significant. Even here it is unlikely that the space charges between cloud and earth would, under prevailing conditions, produce a reversal of sign of the potential gradient.

In a storm developing over the instruments before the cloud reaches cumulo-nimbus proportions, the gradients are generally not more than a few times the fair-weather gradient in magnitude. The gradients begin to increase rapidly within a few minutes before the first intracloud strokes occur. From the first rapid increase of gradient until the first discharges occur between cloud and ground and, until the first rain sheets develop, the only space charge introduced that will appreciably affect the gradients at the surface must result from corona discharge from surface objects. The space charge thus formed may decrease the magnitude of the surface gradient but will not reverse the sign of the gradient.

Both the sign and the magnitude of the recorded gradients should be correct in front of a storm already developed and advancing toward the instrument field.

The situation is more complicated in the case of a well-developed thunderstorm over the field, but the treatment of the data is such that errors due to this condition can be avoided, as will appear in Concluding Remarks.

(3) The assumptions made in calculating the magnitude and the position of charges dissipated by lightning strokes are: (a) The charges involved in the strokes are concentrated or are essentially spherical in distribution; (b) the

earth is an infinite conducting plane; and (c) the stroke does not involve gross redistribution of charge outside of the charge regions actually drained by the stroke.

Again, the justification of these assumptions is based on experimental observations. In the case of a large number of strokes, the pattern of the potential-gradient changes on recorders not directly under the storm is consistent with the dissipation of a single charge center or two charge centers of opposite sign. In the case of about two-thirds of the strokes in a storm, the situation is too complicated for analysis with only eight recorders. The existence of these complicated discharges involving many centers in time sequence is amply checked by many visual and photographic observations on strokes. Because the maximum spread of the recorder positions north and south is 10 miles and east and west is 8 miles, the distances between the charge region and the distance recorders is large by comparison with any reasonable dimension of a charge volume within the cloud affected by a single stroke. The assumption of a concentrated charge is valid, therefore, in a large percentage of the cases.

No measurements have been made on the conductivity of the ground at Albuquerque under varying conditions of moisture, and no direct evidence is available on the question of whether any gross redistribution of charge occurs during strokes outside of the regions directly connected by the stroke. That these points do not affect the measurements seriously is evidenced by the fact that a large number of measurements taken under different conditions of soil moisture and under different meteorological conditions always produce a large number of potential-gradient changes, the analysis of which yields the same solution for heights of positive and negative charges. Also, the order of magnitude of calculated charge transfers is approximately the same for different storms, similar in height above ground and in intensity.

It is not the purpose of this study to present precise measurement of charge magnitude or position. It is felt that the very nature of the phenomena preclude precise measurements. The aim of the study is rather to give unambiguous information as to the character of the thunderstorm and to present quantitative data that are correct in order of magnitude.

DATA ON STORMS OBSERVED DURING AUGUST 1939

By means of visual and photographic observations and data from the eight potential-gradient recorders, a study was made of eight storms occurring during August 1939. Figure 6 is a map of the instrument field and the surrounding territory. The positions of the potential-gradient recorders are indicated by dots and the corresponding recorder numbers. The location of the motion-picture camera is shown in the lower left-hand corner. The origin of the polar coordinate system is at the airport station from which all visual observations were made. The reference line $\theta = 0^\circ$ is north with values of θ increasing in the clockwise direction. The coordinate R is given in miles from the airport station. For location of charge structures a cylinder coordinate system is used. The symbols R and θ have the foregoing meaning and H is the height in miles above the surface. Because all points on the map except the mountains at the eastern edge and a mesa at the western edge have the same elevation within 400 or 500 feet, the surface is treated as a plane.

Smoothed time records of the potential gradients at all instruments for the storms of August 25, and August 20, which were studied in detail, are shown in figures 7 and 8. Reference should be made to these figures for trends of gradients accompanying changing storm conditions described in the following text.

Table I includes the changes in potential gradients at the instrument locations as caused by 32 strokes in the storm of August 25. The approximate magnitude and location of the charges involved in these strokes as determined from an analysis of the potential-gradient changes is also given. It should be noted that, in all cases in which the observers at the airport station observed the stroke visually and heard the resulting thunder, the estimated distance of the nearest part of the stroke as calculated from the thunder data checked the calculated distance to the charge structure.

The strokes reported in table I were selected because the potential gradient changes exhibited were characteristic of the particular interval of the storm during which they occurred. Data were actually taken for 74 strokes in this particular storm, but a satisfactory analysis for a single charge or a dipole structure could be made in only 32 of these cases. It has been found, in general, that about one third of the strokes for which data are taken yield to analysis when eight recorders are used. It should be noted that strokes for which data are ordinarily taken are the medium-sized or large strokes. The gradient changes due to small strokes within the cloud frequently do not record on enough instruments to make an analysis possible.

In the following text, the description of the storms is divided into convenient intervals. The time as given at the beginning of each paragraph indicates the beginning of the interval.*

Table IIA gives the calculated elevation of the height of the cloud base and the 0°C isotherm on days for which storm descriptions are given. These calculations were made from temperature and humidity data; a dry adiabatic lapse rate was assumed to the cloud base and a pseudoadiabatic lapse rate was assumed from the cloud base to the 0°C isotherm. Table IIB gives wind data for the eight storm days.

Storm of August 25, 1939

Cumulo-nimbus developement occurred over the Sandia Mountains to the northeast of the field in the early afternoon starting about 1 p.m. Small gradient changes were recorded for the larger strokes of this development, but the potential gradients over the field were near zero. Between 2 and 3 p.m., cumulus clouds began to develop over the eastern edge of the instrument field and became towering cumulus or early cumulo-nimbus at the end of this period.

2:54 p.m.: A tall cumulus cloud with maximum height of 5.4 miles centered over recorder 5. (See fig. 6.) The cloud base was 1.5 miles above the surface. The gradients initially nearly zero, began to go rapidly negative on recorders 5, 1, and 7 at about 2:58 p.m. (See fig. 7.)

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* The writers regret that the storm data given in the following testare complicated and extremely tedious. It is to be remembered that the descriptions of the storms have been condensed from a large volume of notes and from the photographic records of the clouds. Discussion of several of the storms has been reduced to a minimum, but it seems necessary to give relatively complete information on one or two storms for the purpose of facilitating a critical examination of the conclusions given later in this paper.

3:00 p.m.: The first strokes within the cloud were recorded electrically a few seconds after 3:00 p.m. and 18 strokes were recorded between 3:00 and 3:06 p.m. at a mean frequency of three per minute. Thunder was heard only once and no lightning was observed at the airport station less than 4 miles from the region under the active charge-generating center. Strokes 1, 2, and 3 in table I were selected as representative of this interval. The analysis of the strokes indicated that the active center was located at a height of 3 to 4 miles above a circle of radius 1 mile with center at $\theta = 75^\circ$, $R = 3$ miles. (The coordinates refer to fig. 6.) In this interval the cloud base was included by the lines $\theta = 20^\circ$ and $\theta = 120^\circ$, R varying from 0 to 7 miles. The maximum value of R occurred at $\theta = 45^\circ$.

3:06 p.m.: The first rain sheets were observed at 3:09 p.m. A heavy rain sheet was located at $\theta = 25^\circ$ to $\theta = 43^\circ$, and $R = 3$ miles, and a light rain sheet from $\theta = 55^\circ$ to $\theta = 75^\circ$ at $R = 4$ miles. The height of the cloud top was approximetely 5.6 miles, as determined from the photographs. The stroke frequency was 2.7 per minute and the active center was approximately located by the coordinates $\theta = 65^\circ$, $R = 4$ miles, $H = 3$ to 4 miles. Eight strokes, 4 to 11, in table I were analyzed for this interval. Occasional thunder was heard. The first cloud ground stroke was observed at 3:11:48 p.m.

3:12 p.m. The rain sheet from 25° to 45° continued heavy. The cloud base increased somewhat, extending about 0.5 mile farther west than before. The maximum cloud height was 5.7 miles. The stroke frequency fell to 1.7 per minute; The active center was located at 70°, 4.5 miles, at a height of 3 to 3.5 miles. The strokes were principally within the cloud during the interval. Three strokes, 12 to 14, occurring in this interval were analyzed.

A large cumulus cloud at 145°, 4 miles was observed.

3:18 p.m.: The rain sheet centering at 27°, 3 miles, was much lighter than before. The cloud height was 5.5 miles. The edge of the cloud base now passed through the following points: $\theta = 0^\circ$, $R = 2.5$ miles; $\theta = 45^\circ$, $R = 7$; $\theta = 90^\circ$, $R = 4$; $\theta = 225^\circ$, $R = 0.5$. The stroke frequency continued at about 1.5 per minute with the active center at $\theta = 70^\circ$, $R = 3$ to 4 miles, $H = 3$ to 4 miles. Strokes 15 and 16 occurred in this interval. The center of the growing cumulus to the south was estimated to be at 155°, 3 miles.

3:24 p.m.: The horizontal extent of the cloud remained essentially unchanged. The rain sheet at 27° was somewhat diminished in intensity. The stroke frequency was about 1.7 per minute. A larger number of cloud ground strokes, including 17, 18, and 19, occurred during the interval. Analysis of these strokes indicated that the active center was at 50°, 3.5 miles; 2.5 to 3.5 miles above the surface. The cloud to the south had an altitude 5.4 miles, and an increased horizontal extent.

3:30 p.m. The extent of the cumulus cloud over and to the northeast of the station showed relatively little change, except that it had extended to a distance of 8 miles at 30°. The stroke frequency was 1.7 per minute.

3:36 p.m. The rain sheet at 35° was growing much heavier during the interval. The stroke frequency fell to 1 per minute and no strokes were analyzed. The cumulus cloud, southeast of the station, was rapidly approaching the cumulo-nimbus stage.

3:42 p.m.: The rain sheet at 36° continued and one ground flash was observed at 40°. Lightning activity in this storm decreased nearly to zero. The cloud to the southeast had developed into definite cumulo-nimbus form with an extensive rain sheet from 105° to 190°, the nearest portion of which was 3 miles at 140°. Shortly before the appearance of this rain sheet, the gradient on recorder 7 went rapidly negative. (See fig. 7 for the gradient trends on all instruments at this time.) The stroke frequency in this storm averaged more than 3 per minute during this interval. Frequent thunder to the south was heard at the airport.

3:48 p.m.: The storm to the northeast showed no lightning activity and only light scattered rain. The storm to the southeast was very active with a heavy rain sheet between 135° and 180°, the nearest part of which was 3 miles from the airport. The stroke frequency increased to more than 4 per minute. Frequent thunder to the south and southeast was heard at the airport. No cloud ground strokes were observed during the interval.

3:54 p.m. There was relatively little change since the last interval, except that the bases of the two clouds had merged and the entire eastern half of the sky was overcast. The rain sheet continued heavy between 135° and 180°. The northern edge of the rain sheet was now close to the airport station. The stroke frequency fell slightly to 3.5 per minute, and one cloud ground stroke was observed at 160°, 5 miles. Frequent thunder was heard to the southeast.

4:00 p.m.: The heaviest rain sheet remained at the previously reported position (135° to 180°) although light scattered rain was observed under most of the eastern section of the cloud from 30° to 135°. Stroke frequency fell to 2.7 per minute. Cloud ground stroke 21 was observed. There was frequent thunder from the southeast.

4:06 p.m.: The conditions during the interval changed relatively little, except for a slight decrease in stroke frequency.

4:12 p.m.: A heavy rain sheet from 120° to 150° developed at an estimated distance of 4 miles. The negative gradient on recorder 7, which had fallen during the decreasing storm activity again became markedly negative and the stroke frequency rose abruptly to 3 per minute. Four cloud ground strokes, including 22, were observed.

4:18 p.m.: The rain sheet reported in the previous interval continued heavy; lighter rain was falling between it and the airport station. The stroke frequency again fell to 2.5 per minute. Four cloud ground strokes, including 23 and 24, were observed.

4:24 p.m.: Little change was observed in the cloud base or the rain sheet. The stroke frequency continued at 2.5 per minute. Two cloud ground strokes, 25 and 26, were observed.

4:30 p.m.: Stroke frequency continued at 2.5 per minute. Three cloud ground strokes, including 27 and 28, were observed. Cumulus clouds extending from 200° to 310° along a north-south line about 8 miles west of the station developed during this interval.

4:36 p.m.: Two rain sheets from 95° to 112° and from 125° to 165°, heavy at 102° and 160°, respectively, were recorded. The stroke frequency fell to 1.3 per minute. Two cloud ground strokes, 29 and 30, were observed. A towering cumulus, perhaps early cumulo-nimbus, was observed at 240°, 7 miles; the top was approximately 5 miles above the surface.

4:42 p.m.: The stroke frequency in the southeast storm fell to 1 per minute. One cloud ground flash was observed. The cloud at 240° developed a rain sheet. Occasional lightning was observed. Stroke frequency in this storm was probably greater than 1.5 per minute.

4:48 p.m.: The rain sheet to the south-southeast continued light. The stroke frequency in this storm was less than 0.5 per minute. The clouds previously mentioned between 200° and 310° developed into towering cumulus or cumulo-nimbus. The cloud at 240° had moved, or developed, toward the east. The nearest part of its rain sheet was observed at 220°, 6 miles (estimated). The stroke frequency as indicated by the recorders was approximately 1 per minute; no lightning was visually observed.

4:54 p.m.: The activity in the storm to the southeast had greatly diminished. The rain sheets were extensive but very light. The negative potential gradients at recorders 1, 5, and 7 were decreasing. The negative gradient on recorder 2 was increasing with the approach of the growing southwest storm.

5:00 p.m.: The negative gradient at recorder 7 approached zero. The rain sheet in the southwest storm was recorded as extending from 208° to 230°, at 6 miles (estimated). The stroke frequency was estimated at 1 to 1.5 per minute. No lightning strokes were visually observed.

5:06 p.m.: During this interval the sky became completely overcast. Two strokes were observed at 255°.

5:12 p.m.: The storm in the vicinity of the station had apparently dissipated. The gradients at all recorders, except recorder 2 close to the southwest storm, were nearly zero. The rain sheet at 223° remained nearly stationary at a distance of 5 to 6 miles.

5:18 p.m.: Conditions remained nearly the same. Several distant strokes, including 31, were observed between 200° and 300°.

5:24 p.m.: Several distant strokes, including 32, were observed between 208° and 312°.

5:30 p.m. to 6:00 p.m.: The activity of all nearby storms diminished. A storm, centering at 300°, developed several miles west of the field and moved slowly toward the field, with diminishing activity. Toward the end of the interval, it had approached sufficiently close to produce positive gradients on the western recorders before it dissipated shortly after 6:00 p.m.

Storm of August 20, 1939

The afternoon was characterized by widespread and intense thunderstorm activity. Between 2:00 and 3:00 p.m., an extensive series of storms developed between 250° and 330° from 10 to 20 miles west of the instrument field and moved toward the instrument field. Between 3:00 and 3:30 p.m. frequent lightning was observed between 260° and 325°. A few of the larger and nearer strokes were recorded electrically by the field instruments.

Beginning at 3:12 p.m. a series of storm centers affected the instrument field. The paths of the active centers of these storms are shown in figure 9. Roman numerals are assigned to each active storm center affecting the field and the letters refer to the approximate center of the active region at corresponding particular time. The time intervals between the successive storm positions shown in the figure is 12 minutes.

Between 2:00 and 3:00 p.m. the sky above the instrument field was overcast by high clouds. After 3:00 p.m. the field was gradually covered by lower clouds developing over the field or moving in from the west. At 3:45 p.m. the sky was completely overcast except between 120° and 180°. After this time the position of active centers was determined by positions of greatest lightning activity, rain sheets, or both.

A summary of the observations from 3:12 to 5:12 p.m. is given below by intervals of 12 minutes. All times are after noon.

3:12 - Position A

Storm I was first observed at positon A (see fig. 9) as a large cumulus or an early cumulo-nimbus cloud. No rain sheet appeared at this time. The stroke frequency was probably zero, but the storm produced small negative gradients at recorder 4.

3.24 – Position B

Storm I was a large cumulus or cumulo-nimbus cloud. The stroke frequency was less than 1 per minute with the storm still producing negative gradients at recorder 4.

3:36 – Position C

Storm I was a cumulo-nimbus cloud. The stroke frequency was less than 1 per minute. (See fig. 8(b) for the negative gradients on recorders 4, 6, 8, and 3.) It is possible that there was a second development south of recorder 4. The northern sky was overcast at this time. The rain sheet centered over C.

3:48 – Position D

Storm I: The rain sheet had disappeared. No further observations were made on this inactive storm.

Storm II: A heavy rain sheet appeared. An analysis of strokes that occurred during this period indicates positive charges at 4 miles and negative charges 2 miles above the surface. The positive charges were displaced 1 to 2 miles southeast of the negative center.

Storm III: An active lightning center had developed at position D. Seven cloud-ground strokes were observed. The gradients in the southwest section of the field were becoming positive.

4:00 – Position E

Storm II: Twenty-two strokes were visually observed. The positive gradient at recorder 6 remained constant, while the negative gradient at recorder 4 increased. Stroke analysis indicated that the positive charges were 3.5 miles above the surface; the negative charges were 2 miles above the surface. The positive charges were displaced to the southeast of the negative charges. The total stroke frequency recorded electrically was between 3 and 4 per minute.

Storm III: Five strokes were visually observed. The total stroke frequency was between 1 and 2 per minute. The gradients on recorder 2 went sharply negative about 4:06 p.m.

4:12 – Position F

Storm II: Fourteen strokes were visually observed. The stroke frequency fell from between 4 and 5 per minute to 1.5 per minute during the 12-minute interval. The gradient at recorder 4 went sharply negative and became unreadable because of rapid fluctuations with the closer approach of the storm. The gradients over the entire field were strongly positive except in the vicinity of recorders 4, 3, and 2, which were near active centers.

Storms III and V: The situation was complicated by the close proximity of these storms. There were six strokes observed between 250° and 270°. Thunder placed the position of storm III at F. Two strokes were observed at 290°. This result, with the rapid growth of negative gradients on recorder 3, suggested development of a storm close to recorder 3, designated storm V. The combined stroke frequency of the two storms was about 3 per minute.

4:24 – Position G

Storm II: Four strokes were visually observed. The stroke frequency had again increased to 2.5 per minute. The gradient at recorder 4 was still unreadable.

Storm III: Storm III was at position G. The strokes were within the cloud, two of which were observed visually about 1 mile west of the airport. These were the last strokes observed in this storm. The charge structures analyzed showed inclined dipoles with negative charge 2 miles high and positive charge 3 miles high and 2 miles east of the negative charge. The subsequent course of the storm could not be traced.

Storm IV: A heavy rain sheet developed between 50° and 70°, centering at G. Four strokes were observed visually between 70° and 90° estimated from 6 to 8 miles. The gradients on recorder 1 became negative.

Storm V: The heavy rain sheet from 280° to 300° was estimated to be about 4 miles from the airport. Six strokes were visually observed. The probable stroke frequency was 3 to 4 per minute. The gradients on recorders 3 and 6 went rapidly negative.

4:36 – Position H

Storm II was apparently inactive and position H was extrapolated from the storm's previous motion. Recorder 4 became positive. There were no further observations on this storm.

Storm IV: Four strokes were visually observed between 70° and 90°, the distance being estimated at 8 miles. Recorder 1 reached a negative maximum and started to decrease with the recession of the storm from the field and with its decreasing intensity.

Storm V: There was a marked increase in activity. Eighteen strokes were visually observed between the airport and recorder 3. The total stroke frequency was about 3 per minute. A heavy rain sheet extended to the airport. The gradient at recorder 6 dropped to zero, and the negative gradients on recorders 3 and 2 decreased in magnitude. The positive gradient on 8 decreased to zero.

4:48 – Position I

Storm IV: No activity was observed.

Storm V: Thirteen strokes were visually observed within a radius of 1 mile of position I. The total stroke frequency was about three per minute. The stroke analysis indicates negative charges 2 miles and positive charges 4 miles above I. One cloud-ground stroke was observed. Heavy rain occurred at the airport. Recorder 1 and 5 became negative with eastward progress of the active center.

5:00 – Position J

Storm V: The stroke frequency was less than 1 per minute. The approximate position of the active center was at J. All the recorders at this time were negative except recorder 2. Distant lightning was observed from 90° to 120°, which was probably unrelated to any of the storms near the field.

After 5:00 p.m., it was not possible to locate any centers of activity. Occasional thunder was heard for 20 minutes but no lightning was observed in the vicinity of the field. No explanation of the variations in the gradients between 5:00 and 6:00 p.m. can be given because of insufficient information for the analysis of a very complicated structure.

Storm of August 2, 1939

The day was characterized by cumulo-nimbus development from late morning until late afternoon. About 1:50 p.m., rapid cumulo-nimbus development was first observed at 0°, 5 miles. At this time, the cloud base was about 1.5 miles above the surface and the top was at 4.5 miles. Recorders 1 and 5, nearest the storm (the northern recorders were not in operation), indicated negative gradients increasing from 1:50 to 2:00 p.m. and decreasing to zero at about 2:10 p.m. During the period of growth, the stroke frequency was about 1 per minute falling nearly to zero at 2:10 p.m. By 2:25 p.m., the storm was no longer active and the gradients were slightly positive.

At 2:30 p.m. a second rapid cumulo-nimbus development was observed in the vicinity of recorder 2. The cloud base was 1.5 miles and top 3.5 miles high. By 3:00 p.m. the top had reached 6 miles when a limited ceiling prevented further observations; between 2:30 and 2:40 p.m., all the gradients were negative and remained negative until between 3:25 and 3:55 p.m. During the period that the storm was over the south part of the field, the stroke frequency was at a maximum, reaching about 2.5 strokes per minute. As the stroke frequency dropped to zero around 3:30 p.m. all gradients decreased and became zero or positive. All gradients were approximately zero at 4:45 p.m.

Storm of August 6, 1939

At 2:35 p.m. a cumulo-nimbus cloud developed at 235°, 7 miles. The cloud bases were approximately 1.5 miles high.

Between 2:30 and 2:45 p.m., gradients at recorders 3 and 7 became negative and slightly increased. At 2:55 p.m., two other cumulus developments were observed at 185°, 6 miles and 250°, 5 miles, respectively. The tops of these clouds were approxmiately 4 miles above the surface. Corresponding to the continuation of these developments, there was a rapid increase in the negative gradients between 2:50 and 3:00 p.m. on recorders 3 and 7. Shortly after 3:00 p.m., the sky became overcast and further cloud observations were impossible. The gradient on recorder 3 returned to zero at about 3:40 p.m. and subsequently became positive. The gradient on recorder 7 remained negative, either due to the westward motion of the storm south of recorder 3, or to a new development near recorder 7. Recorder 7 finally became positive at about 3:55 p.m. Both recorders 7 and 3 returned to zero about 4:45 p.m. The storm intensity on this day was very weak, the stroke frequency not exceeding 1 per minute in the nearby storms. Recorder 4, approximately 14 miles from these developments, showed slightly positive gradients until 3:45 p.m. when the gradient became markedly positive and then markedly negative around 4:40 p.m. The last observation probably does not correspond to the storms affecting recorders 3 and 7.

Storm of August 9, 1939

Between 2:00 and 2:30 p.m., a storm developed at 250°, 10 miles (estimated) and proceeded toward the southwest edge of the recorder field.

2:42 p.m.: The storm was 6 to 7 miles (estimated) from the airport when the gradients at the nearest recorders, 3 and 8, became positive.

2:54 p.m.: The gradients at 3 and 8 became negative with the closer approach of the storm to position A of figure 10 and the gradients at the reamining recorders became positive in succession. Recorders 2 and 6 were positive. The total stroke frequency was 4 per minute. Two strokes per minute were visually observed.

3:00 p.m.: The stroke frequency fell to 2 per minute and the negative gradients at recorders 3 and 8 fell slightly. The positive gradients at the remaining recorders increased.

3:24 p.m.: The storm showed renewed activity with an active center at position B (fig. 10). The stroke frequency increased to 5.5 per minute. The gradients at 3 and 8 became rapidly negative reaching values of 150 to 200 volts per centimeter. The positive gradient at recorder 7 fell to zero and again increased slightly, and the positive gradients on the remaining recorders decreased slightly.

3:36 p.m.: The active center had reached 280°, 2 miles, and the positive gradients at recorders 5 and 7 were decreasing rapidly and at recorder 1, slowly. The gradients at recorders 3 and 8 fluctuated but remained negative. The stroke frequency had again fallen to 2 per minute.

3:48 p.m.: The stroke frequency fell below 1 per minute as the active center moved north of the airport station to position C. The gradient at recorder 3 fell rapidly to zero and the gradient at 8 decreased. The gradients at recorders 5 and 7 became negative and subsequently positive.

4:00 p.m.: There was a slight increase in activity of the storm now at position D. The stroke frequency rose to 1 per minute. The gradients at recorders 3 and 8 became positive. The gradient at recorder 7 remained positive and the gradients at recorders 1 and 5 became negative.

4;12 p.m. to 5:00 p.m.: The last-mentioned increased activity was short-lived. The stroke frequency fell to 0.2 per minute between 4:12 and 4:24 p.m. and then to zero. There were two oscillations of the field that could not be interpreted in the absence of observations on lightning strokes, concentrated rain sheets, or cloud structure. The sky was overcast.

Storm of August 10, 1939

The afternoon was characterized by the development of many small storms moving from southwest to northeast. No storm achieved the proportions of the storm of August 9, and the lightning strokes were relatively infrequent throughout the afternoon.

At 1:30 p.m., a towering cumulus was observed at position A (fig. 11). At 2:00 p.m., this cloud now at B had developed to the cumulo-nimbus stage and the gradient at recorder 4 became rapidly negative reaching a negative maximum at 2:15 p.m. At 2:00 p.m. recorder 6 became negative.

At 2:10 p.m., a cumulo-nimbus cloud with a light rain sheet was observed at C. Recorder 3 became slightly negative. This storm increased in size and moved to the northeast. At 2:30 p.m., a light rain sheet appeared at B and at 2:35 p.m. it had extended to recorder 6. Beginning at 2:20 p.m., recorders 3 and 6 became rapidly negative. Recorder 8 became slightly positive at 2:25 p.m. and rapidly negative after 2:30 p.m. Recorder 4 indicated slightly increased negative gradients between 2:30 and 2:40 p.m., possibly caused by this storm.

The negative gradient at recorders 3 and 6 reached their maximum values at 2:40 p.m. and at 8 at 2:50 p.m., consistent with the northeast motion of the storm. Recorders 5 and 7 indicated slightly negative gradients between 2:40 and 3:00 p.m., probably due to the storm between the positions D and E. The storm reached position E at

3:10 p.m., after which no further observations on it were made. Recorder 3 became slightly positive after 3:00 p.m.

Between 3:00 and 4:00 p.m., the negative gradients observed at recorders 5 and 7 may have been produced by a large cloud moving in from the southwest, reaching the airport at 3:00 p.m. and passing over the extreme southeast field. This cloud had no rain sheet and gave no visual evidence of lightning activity. No certain evidence of its effect was obtained.

At 3:30 p.m., the gradients were zero at recorders 7, 6, and 3, and slightly negative at recorders 5, 8, and 4. At 3:30 p.m., the negative gradient at recorder 4 began increasing rapidly reaching a maximum negative value at 3:40 p.m. At about 3:45 p.m., a rain sheet was observed at position F. The gradients again decreased to zero at 4:00 p.m.

Storm of August 13, 1939

The large storm region that affected the recorders in the latter part of the afternoon developed in the northwest, centering at 330° approximately 20 miles at about 2:30 p.m. The storm region moved toward the recorder field, with high clouds passing over the field at least an hour before lightning activity reached the field. Owing to the extent of the cloud and the variability of its lightning activity and rain sheets, it was not possible to follow any one active center for a long period of time. It was possible, however, to observe the effects of a number of active centers during the storm. Throughout the storm period, frequent lightning was observed at some distance from the field. Only those centers that were close enough to affect the recorders are described. The gradients at 5-minute intervals are given for all recorders in table III.

Between 3:15 and 3:30 p.m., 10 strokes were observed between 310° and 340° at distances from 12 to 15 miles. The gradients at all recorders were zero or positive and increasing in a positive direction. The gradients were greatest at recorders 6, 4, and 3 and smallest at recorders 7, 5, and 1. At 3:15 p.m., the western half of the sky was overcast with heavy clouds having bases about 1.2 miles above the surface.

Between 3:30 and 3:45 p.m., the center produced no visible flashes. Cloud activity continued, but stroke-frequency estimates were unreliable. The gradients were not greatly changed from their values at 3:30 p.m. except that recorder 1 showed small negative values during the interval.

From 3:45 to 4:00 p.m., the positive gradients at recorders 4 and 3 decreased, remained nearly constant at recorders 2, 8, and 5, but increased at recorders 1 and 7, probably due to the motion of the charges from the now inactive center toward and over the field.

Shortly after 4:00 p.m., the gradients at recorders 8, 3, 6, 4, and 1 became negative, most rapidly at recorder 8. At 4:08 p.m., rain sheets were observed at 320°, 340°, and 15° and strokes occurred in a region centering at 0°, 5 miles.

From 4:15 to 4:40 p.m., this active center moved to 40°, 3 miles. Eight strokes were observed. Gradients at recorders 8, 6, 3, and 1 remained negative, at recorder 8 increasing, and at recorder 1 decreasing at the end of the interval. The gradients at recorders 2 and 5 remained positive with little change. Recorder 4 became positive about 4:25 p.m. A rain sheet was observed between 0° and 50°, heavy at 10° and 40°, at about 3 miles.

From 4:30 to 4:45 p.m., the rain sheet became more extensive, spreading from 350° to 80° and reaching the airport station. Twenty-two strokes were visually observed between 0° and 70°. The strokes nearest to the station about 2 miles away were within the cloud. Two ground strokes were observed between 3 and 4 miles away. Fourteen of the strokes were too distant to produce audible thunder. Apparently, the active region previously reported had increased in intensity and one or more new centers had developed between the northeast part of the field and the mountains. The gradient at recorder 8 was strongly negative, and less so at 3 and 6.

Between 4:45 and 5:00 p.m., a heavy rain sheet reached the airport station. Heavy rain was visible in all directions except between 200° and 260°. Twenty-two strokes centering at 0°, 2 miles were observed. The gradients at recorders 4, 1, and 2 were positive. Recorder 5 became negative during the interval. The gradient at recorder 8 was negative until 4:55 p.m., after which it became positive.

Shortly after 5:00 p.m., the lightning activity ceased and the gradients gradually approached zero after some fluctuations.

Storm of August 16, 1939

The afternoon was characterized by widespread thunderstorm activity. Between 3:40 and 4:12 p.m., the sky became overcast over the entire recorder field. The location of active regions became impossible except by noting position of rain sheets and lightning activity. Rain sheets were first observed over the mountains and later appeared over the field. The westward development of the rain sheets undoubtedly was not due to a westward motion of a storm but rather to the development of the storm over the field, because the winds at all levels were essentially from the north and the westward progress of the rain sheets was too rapid for any motion of storm centers. The gradients at all recorders were nearly zero before 4:00 p.m. At about 4:00 p.m., the gradient at recorder 6 went rapidly negative, reaching values of 150 volts per centimeter by 4:05 p.m., owing to a cumulo-nimbus development near A. (See fig. 12.) By 4:15 p.m., the negative trend at recorder 6 was followed by a rapid negative trend at recorders 1 and 5, owing to a storm developing at C. At 4:20 p.m., a rain sheet appeared near C and at 4:30 p.m., a rain sheet developed over Albuquerque with a center at B. During the interval, recorders 3 and 2 indicated slight negative gradients.

Between 4:30 and 5:00 p.m., frequent lightning strokes were observed over the recorder field between C and D. During this time, all recorders were negative including recorders 2 and 3, which showed increasing negative gradients after 4:30 p.m. The active center of the storm and the rain sheet proceeded from D to E between 5:00 and 5:15 p.m. and finally dissipated after 5:15 p.m.

Between 5:20 and 5:35 p.m., all recorders became positive. At approximately 6:00 p.m., all recorders again indicated negative gradients (small except at recorder 1), due apparently to an active center developing in the vicinity of 1 and moving toward the southwest. This center did not show lightning activity, possibly due to the decrease of surface heating in the late afternoon.

DISCUSSION OF RESULTS

The storms studied during August 1939 in the vicinity of Albuquerque were similar in vertical dimensions. The cloud bases were all approximately 1.5 miles above the surface; about 2.5 miles above sea level. No lightning activity was observed in any cloud with a top less than 4.5 miles above the surface, that is, with a cloud depth of less than 3 miles. The well-developed storms had maximum heights between 5.5 and 6 miles above the surface.

The principal differences between the various storms lay in their horizontal extent and intensity. The storms with the greatest maximum height were the most extensive and most active. The most extensive storms, those of August 13 and 20, had more than one active center.

The similarity of vertical dimensions simplifies the problem of comparison of charge positions within the cloud on different thunderstorm days. Caution must be exercised, however, in using the calculated heights of charges above the surface of the earth for Albuquerque storms in regions with characteristically lower clouds. The position of the thunderstorm charges with respect to the 0° C isotherm or the cloud base may be of more physical significance than height above the surface. Even though quantitative measurements on charge position may not be applied to other regions without correction, these observations on thunderstorm structure directly related to the fundamental charge-generating processes should be generally applicable.

All the evidence obtained points to the conclusion that, in the active charge-generating region of the storm, the positive charge is higher and the negative charge is lower in the cloud. The conclusion is supported by the following observations:

1. Whenever a cumulo-nimbus cloud developed over the field, the first gradients observed were always negative at the recorders close to its base. The gradients were largest and grew most rapidly underneath or close to the region of most rapid vertical development of the cloud. The negative charges in the cloud overhead dominated the nearer field and hence must have been lower in the cloud in the formative stage of the cumulo-nimbus. The observation is particularly significant because at the time the first gradients are observed the region between cloud and ground is not affected by space charges.

2. Analysis of the gradient changes produced by the first lightning strokes in a storm show that the charge structures dissipated consist of vertical or inclined dipoles with a lower negative charge and an upper positive charge having a vertical separation of a mile or less. These calculations give support to the existence of the charge structure described in section 1.

3. In the case of well-developed storms that moved across the recorder field, the gradients at the recorders first became positive while the active center was at some distance. As the storm approached, the gradients became larger. When the active center came still closer, there was a reversal of the sign of the gradient. The gradients remained negative while the active center was near or above the recorders. As the active center moved away from the recorders a second reversal occurred, that is, the gradients again became positive. The reversal after the active center had passed was sometimes farther from the active center than the first reversal. This pattern of gradient trends was characteristic of every well-developed moving storm observed in August 1939, which was well developed at the time it affected the field instruments. An examination of the character of the surface-gradient pattern produced by a dipole structure (see fig. 3) with positive charge farther from surface shows at once that the usual sequence of gradient trends described can be accounted for if the cloud has a higher positive and lower negative charge. The magnitude of the positive gradients and their wide surface distribution in advance of the storm indicates, however, that the upper positive charge is larger and is frequently displaced in the direction of storm motion, with respect to the negative charge. Since the gradient observations are made when space charges exist between cloud and earth, independent check is desirable. This check is supplied by observations and calculations described in sections 4 and 5.

4. In the case of all strokes that could be analyzed, (approximately one-third of those attempted), the lightning stroke discharged one of the following structures:

(a) A dipole within the cloud with positive charge farther from the surface (in the case of a few strokes at the same distance from the surface) than the negative charge, or

(b) A single negative charge in the lower part of the cloud.

These results were obtained by analysis of the gradient changes on recorders at distances of several miles from the active center as well as recorders in the vicinity of the active center. In any one storm the negative charges affected by the lightning strokes were at a characteristically lower elevation than the positive charges. In the moving storms the positive charges involved in the lightning strokes were found to be displaced forward as well as upward from the negative charges in a large number of strokes. These observations are in accord with the qualitative observations of gradient trends in the case of a storm moving over the recorders, as described in section 3.

5. Even though it is impossible to analyze a large number of strokes in the storm with only eight potential-gradient recorders, the relative frequency of positive and negative gradient changes at different distances from the active center should confirm the general charge structure based on other observations. If the gradients due to two charges of the same magnitude at different heights above the surface are compared, it is found that the surface gradients due to the lower charge are larger for points near the charges whereas gradients due to the upper charge are greater for more distant points. (See figs. 2 and 3.) If the positive charges in the active region are higher, their influence will be dominant at distant points and lightning strokes affecting both positive and negative charges will therefore produce negative gradient changes at distant points. Positive gradient changes will be produced only by the discharge of a lower negative charge to ground and will be observed at distant stations only in the case of the larger ground strokes. When the active region is overhead, the strokes will produce only positive gradient changes because the negative charge dominates the field. The sign of the gradient change will be the same for both cloud-ground and intracloud strokes in this case.

Upon examination of the records of well-developed storms that moved into or across the recorder field, it was found that, when the storm center was far from a particular recorder, all but a few strokes produced negative gradient changes. As the storm moved toward the recorder, the negative changes became larger and a larger number of positive changes were observed. As the active center moved within 2 or 3 miles of the recorder, the relative size of the positive changes increased and the positive changes became more frequent than the negative changes. When the storm center was over the recorder, all gradient changes were positive. Finally as the storm center receded from the recorder, the negative gradient changes again became larger and more frequent than the positive changes. This observation also supports the qualitative picture of the structure obtained from the gradient trend and the partial quantitative picture from the stroke analysis described in sections 3 and 4.

The conclusion is in agreement with the polarity of a thunderstorm predicted by C. T. R. Wilson's theory. The results, however, do not offer any conclusive test of the details of the theory. The conclusion is contrary to the prediction of the Simpson theory of thunderstorms, which places the positive charge lower in the cloud than the negative charge in the region of the charge generation.

The conclusion on polarity of the thunderstorm is similar to that reached by Wilson (reference 4) and Schonland (reference 5) on the basis of gradient measurements. The present method, employing a number of potential-gradient recorders, is capable of yielding more definite quantitative information on the various phases of thunderstorm development and overcomes some of the chief objections that have previously been advanced against surface potential-gradient methods.

The results of Simpson and Scrase (reference 6), who measured gradients in thunderclouds with apparatus on free balloons, have been used in support of Simpson's theory. Owing to the fact that the charge structure changes during the balloon ascent as the result of lightning strokes and owing to the fact that the horizontal displacement of the balloon with respect to the active region is difficult to determine when the balloon is within the cloud, the results of Simpson and Scrase do not lead to a clear interpretation of charge structure. This point has been discussed by Byers in reference 7.

Humphreys (reference 8) has recently suggested a modification of Simpson's breaking-drop theory of thunderstorm charges in which the positive charges located on the larger drops are maintained high in the cloud by the strong vertical air currents. The negative charges are first carried upward and then descend outside the main upward current. Humphrey's suggestion would lead to correct polarities in well-developed storms but does not clearly account for the fact that the first gradients observed in a growing storm are negative instead of positive.

Data obtained from several synchronized recorders yield additional quantitative and qualitative information on the charge structure of thunderstorms and changes in charge structure that accompany their growth and decay.

The negative charge centers were found to vary in height between 2.25 and 3.25 miles above the surface of the earth; the positive charge centers were found between 3 and 4.5 miles above the surface. The characteristic height of negative charges was approximately 3 miles and the characteristic height of positive charges was about 4 miles. These heights are, respectively, 1.5 and 2.5 miles above the cloud base.

The magnitude of the charges involved in all types of stroke analyzed varied between 10 and 190 coulombs. The charge magnitude was most frequently found to be between 20 and 50 coulombs.

The first strokes in the early part of the storm were entirely within the cloud and discharged vertical or inclined dipoles. The charge magnitudes were small, and the stroke-path lengths were between 0.5 and 1 mile. Lightning activity usually continued for several minutes in the cloud before the first cloud-ground strokes occurred. In a storm that had been active for some time, the charge magnitudes were larger and stroke lengths of 3 miles or more were not uncommon. In a very active storm, such as the storm of August 20, the number of cloud-ground strokes again decreased and the last strokes were usually within the cloud.

All cloud-ground strokes analyzed transported negative charge from the lower part of the cloud to the ground. Although this observation does not prove that cloud-ground strokes never transport a positive charge to ground, it indicates that, if cloud-ground strokes transporting a positive charge downward exist, they are relatively infrequent. The writers have previously made this observation in another investigation; McEachron (reference 9) and Lewis and Foust (reference 10) using totally different experimental methods have arrived at similar conclusions.

It is of interest to note that, since cloud-ground strokes transport negative charge to the ground, a well-developed storm that has produced many cloud-ground strokes should have an excess of positive charge in the cloud. This excess must account for the fact that the positive gradients have a wide distribution and large magnitudes in the vicinity of well-developed storms. This fact, together with the fact that the positive charges are frequently displaced in the direction of storm motion, accounts for the very large positive gradients in advance of some well-developed storms.

Several meteorological correlations with the charge data are of interest.

The charge structure located in the cloud was above the calculated position of the 0° C isotherm. The charge-generating process occurred in a region of the cloud in which both water and ice particles were probably present. Although it is impossible to draw any definite conclusions on the basis of these results, the observations support the suggestion that the fundamental charge-generating process may be intimately associated with the change of the state of water.

Byers (reference 7) has pointed out that airplane pilots have observed most displays of coronas on their airplanes near the −10° C isotherm and have in that region experienced the greatest difficulty with rain and snow static. The phenomena seem to occur in clouds that are not cumulo-nimbus. In at least one case a pilot observed liquid water in association with ice in the form of fine hail or sleet. On the basis of these observations, Byers suggested that heterogeneous mixtures of ice, liquid water, and vapor might be significant in the charge-generating process.

It is significant to note that the −10° C isotherms lie close to the boundary between the negative and the positive charged regions in the Albuquerque thunderstorms. The −10° C isotherm would therefore be a surface on which large gradients would extend over large areas.

The rain sheets that are ordinarily associated with the transition of a cumulus into a cumulo-nimbus cloud are apparently visible below the cloud level after electrical activity in the cloud is well under way. In the one case (the storm of Aug. 25) in which an accurate time observation on the first appearance of a rain sheet was made, the gradients under the cloud had been negative for 8 or 9 minutes. This interval is of the order of magnitude of the time of fall of large droplets from the top of the charge structure to the cloud base. In other cases, where the observer's attention was particularly directed to lightning observations, it was incidentally observed that the appearance of increased negative gradients preceded or occurred at nearly the same time as the initial appearance of the rain sheet. No rain sheets were observed before the top of the cloud presented the soft appearance usually attributed to ice particles.

The cloud photographs reveal the fact that the vertical flow of air takes place in a pulselike fashion. Each upsurge is associated with increased potential gradients and stroke frequency. In the storms for which it is possible to follow the cloud development, the stroke frequency decreases when the cloud ceases to grow in height or to increase in volume at the top.

CONCLUDING REMARKS

Reference was made in the introduction of the paper to a method of study that would enable the more than usually complicated strokes of a storm to be analyzed. These strokes involve repeated discharges or sequences of discharges that follow in time sequence too closely to be separated by the slow potential-gradient recorders used as indicated in the foregoing discussion. In spite of these difficulties, it appears, however, that the relatively simple and fruitful method of studying charge transfers and charge structure may be achieved by using at least eight fast recorders that operate with sufficient time-resolving power to separate all or nearly all of the individual stroke elements. Photographic measurements with cameras developed by Professor C. V. Boys have shown that most of these individual stroke elements have time separations of more than 0.01 second and many of them have separations of 0.1 second or more.

Early in the summer of 1939 the writers devised a recorder consisting simply of an exposed electrode, similar to devices used in the early work of Wilson, that was connected directly to the element of a rather fast-acting string electrometer. The position of the string was photographed with a camera system similar to that used in the slow recorders except that the film moved about 120 times as fast. The exposed electrode was connected to ground through a high-resistance leak. The time constant for the circuit was made sufficiently long to permit recording the stepped changes in the potential gradient due to repeated discharges and at the same time keep the electrometer from going off scale as a result of slower steady changes in the potential gradient. Four recorders of this type were constructed and installed. These instruments were used on one or two storms as a preliminary test of the method and they give promise of yielding very valuable results for the following reasons.

A series of rapidly repeated lightning strokes is made up of a number of single elements that, in general, take place with appreciable time separation. Each element will, in general, involve transfers between two cloud charges or between one cloud charge and the ground. These simple structures can be analyzed by the method indicated in the introduction of this report. This method of breaking down the most complicated structures should enable one to obtain a relatively complete picture of the charge structure. Following this line of analysis, a cloud-to-ground repeater should resolve itself into a number of elements showing the ground as one pole and, successively, different regions of the cloud as the other pole. An intracloud repeater should be resolved into a succession of dipole strokes.

A stroke analysis of a storm based on this technique should yield extremely valuable information about the active centers of the storm. Centers of charge resulting from the chief charge-separating mechanism of the storm could be indicated as regions most frequently involved in stroke activity. Furthermore, this method of attack will serve to indicate that many charge centers normally found in a well-developed storm are not directly associated with fundamental charge-generating processes. These centers may result from charges transferred within the cloud by convection or residues along the path of lightning discharges during intense activity, or charges on the rain below the cloud. Occasional lightning strokes, such as air discharges, may take place between these accidental centers but the nature of these centers will be betrayed by small stroke activity between them. The method suggested, therefore, is one of studying the charge structure of the storm and the generating mechanism by a relatively complete study of the disruptive transfers of charge within the cloud.

The instruments that were used did not give any indication of the potential gradient under the cloud but indicated merely the changes in this gradient due to lightning discharges. The results of the trial were not significant because only four recorders were used. The technique, however, was satisfactory and suggests an important extension of the method of charge measurement by observing sudden changes in the surface potential gradient.

University of New Mexico,
Albuquerque, N. M., May 4, 1940.

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TABLE I

CHANGES IN POTENTIAL GRADIENTS CAUSED BY 32 LIGHTNING STROKES IN STORM OF AUGUST 25, 1939

		Gradient change (volts/cm)							Positive				Negative		
Number of strokes	Time	1	2	3	4	5	6	7	Q (coulombs)	θ (deg)	R (miles)	H (miles)	θ (deg)	R (miles)	H (miles)
1	3:04:00	19	2	0	0	60	0	6	22	70	2.5	3.5	70	2.5	3.0
2	3:05:09	27	-2	0	0	21	0	6	21	82	3.6	3.5	82	3.6	3.0
3	3:05:36	35	-3	0	0	42	-2	12	37	83	3.3	3.5	83	3.3	3.0
4	3:06:14	25	?	0	0	13	-2	6	27	88	4.2	3.5	88	4.2	3.0
5	3:07:05	42	-2	-5	0	17	0	7	12	84	4.5	4.0	84	4.5	2.5
6	3:07:32	40	3	2	0	19	0	14	22	58	5.4	3.0	64	4.3	3.0
7	3:08:05	47	1	0	0	16	0	8	15	57	5.7	3.5	61	4.7	3.0
8	3:08:32	70		0	0	18	0	14	15	65	7.0	3.5	71	5.3	2.5
9	3:09:34	54	0	0	0	31	0	9	42	82	4.0	3.5	82	4.0	3.0
10	3:10:04	9	10	0	0	80	-3	3	16	42	3.3	4.0	45	2.0	2.5
11	3:10:39	75	-2	0	0	125	0	10	70	61	2.5	3.5	61	2.5	3.0
12	3:13:30	90	-2	0	0	23	0	4	50	74	4.6	3.5	74	4.6	3.0
13	3:15:12	110	-5	-3	-2	66	-2	3	70	56	3.3	3.5	56	3.3	3.0
14	3:16:47	115	0	7	2	56	6	5	33	72	5.8	3.5	59	4.2	3.0
15	3:18:42	120	-3	2	0	96	2	2	25	74	4.3	4.0	65	3.7	3.0
16	3:21:47	80	0	2	0	72	4	1	28	78	4.2	4.0	64	3.5	3.0
17	3:24:00	105	15	13	4	108	71	7	20		Ground		50	3.2	3.0
18	3:24:57	130	7	12	2	108	8	10	17		---Do---		48	3.3	2.5
19	3:28:07	160	9	-5	5	115	8	7	20		---Do---		49	3.6	2.2
20	3:52:36		55	15	0	57	12		75		---Do---		172	4.9	3.0
21	4:02:00		51	18	2	170	12		40		---Do---		139	2.0	3.0

TABLE I. - CONTINUED

		Gradient change (volts/cm)							Positive				Negative		
Number of strokes	Time	1	2	3	4	5	6	7	Q (coulombs)	θ (deg)	R (miles)	H (miles)	θ (deg)	R (miles)	H (miles)
22	4:14:51		29	13	2		12	85	40		Ground		136	3.7	3.0
23	4:19:58	77	28	15	3	166	10	225	50		---Do---		105	3.7	3.0
24	4:23:35	76	63	17	4	200	12	152	31		---Do---		100	1.2	3.0
25	4:26:16	67	55	20	3	206	12	79	24		---Do---		48	.8	2.5
26	4:28:28	160	40	31	5	242	20	120	36		---Do---		83	2.8	3.0
27	4:32:56	148	27	25	4	201	14	190	40		---Do---		102	3.2	3.0
28	4:34:42		8	15	3	135	10	204	40		---Do---		76	2.8	3.0
29	4:37:03	152		13	3	207	10	220	50		---Do---		102	4.0	3.0
30	4:41:12	130	18	13	4	131	13	136	44		---Do---		102	4.3	3.2
31	5:18:09	17	115	31	4		10	13	55		---Do---		206	4.3	3.5
32	5:28:16	14	99	32	2	32	16	60	120		---Do---		214	7.2	3.0

TABLE IIB

WIND VELOCITY FOR EIGHT STORMS

[Velocity in mph at 1:30 p.m.]

August 1939 \ Height above the surface (miles)	0	0.8	1.5	2.1	2.7	3.3	4.0	4.6	5.2
2	ESE12	N8	ENE6	ENE12					
6	WNW11	NW11	NW9	WNW15	WSW11	WSW20	WSW24	W39	W48
9	SW9	SW7	NW9	NW16	WNW18	WSW18	WSW13	W33	W55
10	WSW4	WSW9	W11	WSW17	SW11	SW11	W31	W39	W77
13	SSW13	S9	WSW6	WNW11					
16	NW7	N9	ENE20	ENE22	NE22	N18	NNW16	N13	N22
20	SE24	SSE16	WSW16	WSW27	WSW22	WSW9	W27	WNW20	WNW37
25	SW9	ESE7	E2	ESE4	ESE2				

TABLE IIA

ELEVATION OF CLOUD BASE FOR EIGHT STORMS

Date	Cloud base above the surface		Height of the 0° C isotherm above the surface	
	(ft)	(miles)	(ft)	(miles)
August 1939				
2	6800	1.3	11,400	2.2
6	6900	1.3	11,600	2.2
9	7600	1.4	10,600	2.0
10	9100	1.7	10,600	2.0
13	7600	1.4	11,200	2.1
16	8400	1.6	11,300	2.1
20	7000	1.3	10,400	2.0
25	8500	1.6	10,300	1.9

TABLE III

POTENTIAL-GRADIENT DATA FOR AUGUST 13, 1939

[Potential gradient given in volts per cm]

Time (p.m.) \ Recorder number	1	2	3	4	5	6	7	8
3:00	2	0	2	3	12	7	2	17
3:05	3	0	6	7	15	15	3	25
3:10	4	2	20	11	20	20	5	35
3:15	5	6	30	10	22	15	6	70
3:20	3	15	120	17	30	70	10	155
3:25	7	30	150	25	35	85	25	200
3:30	6	35	150	60	30	95	25	230
3:35	−30	25	170	60	40	90	65	230
3:40	−70	30	150	70	60	80	95	210
3:45	−40	30	150	60	74	78	85	245
3:50	60	35	150	80	92	74		250
3:55	100	35	20	80	83	73		260
4:00	70	30	0	.....	73	70		270
4:05	74	30	−5	.....	70	0		−100
4:10	−40	30	140	−70	68	−12		−75
4:15	−100	30	−40	−80	72	−24		−20
4:20	−97	30	−35		62	−25		−40
4:25	−94	30	−20	40	68	−20		−10
4:30	0	30	−30	50	72	−30		−150
4:35	60	30	−30	50	72			−115
4:40	70	30	0	40	50			−160
4:45	80	12	10	−30	60			−100
4:50	0	30	12	0	−35			−55
4:55	60	17	15	40	−50			
5:00	75	0	0	50	−45	−20	−85	260
5:05	80	20	−35	−70	−15	10	−170	240
5:10	80	−30	−40	−90	−25	40	−210	240
5:15	75	−60	−50	−100	−50	90	−190	240
5:20	30	35	−30	−100	−100	87	−195	230
5:25	85	25	40	.....	−92	45	−200	230
5:30	80	−35	−10	−30	−110	45	−85	170

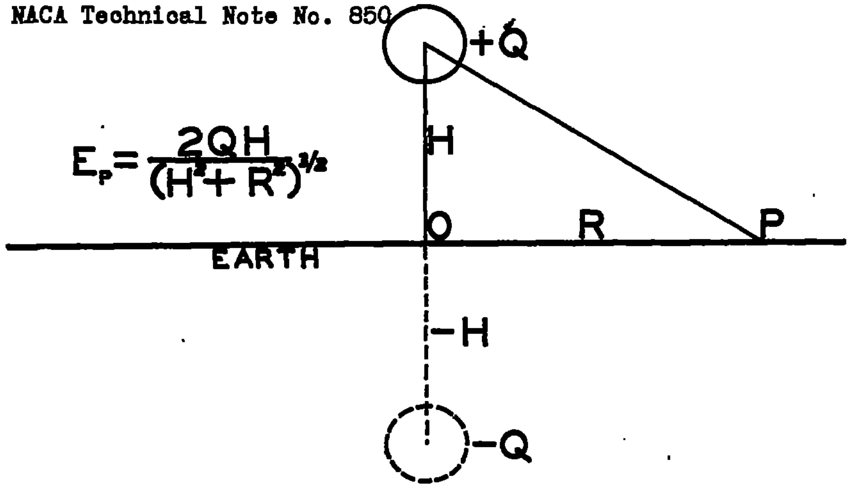

Figure 1.- Surface of the earth as an infinite conducting plane.

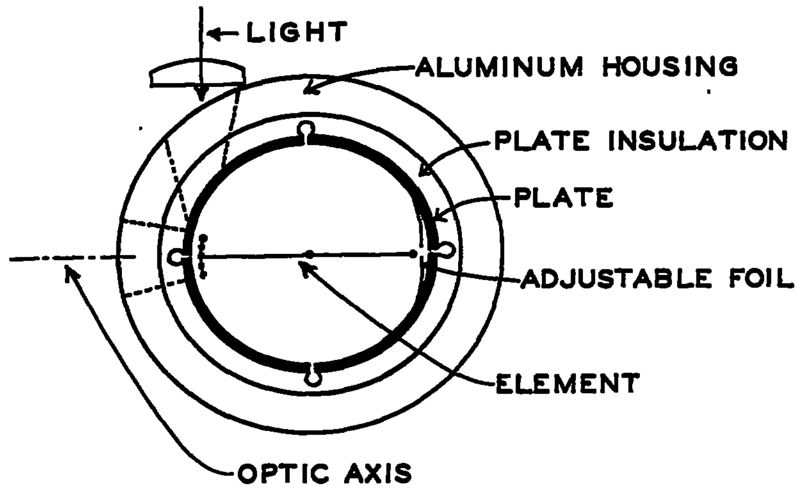

Figure 4.- Schematic drawing of improved electrometer.

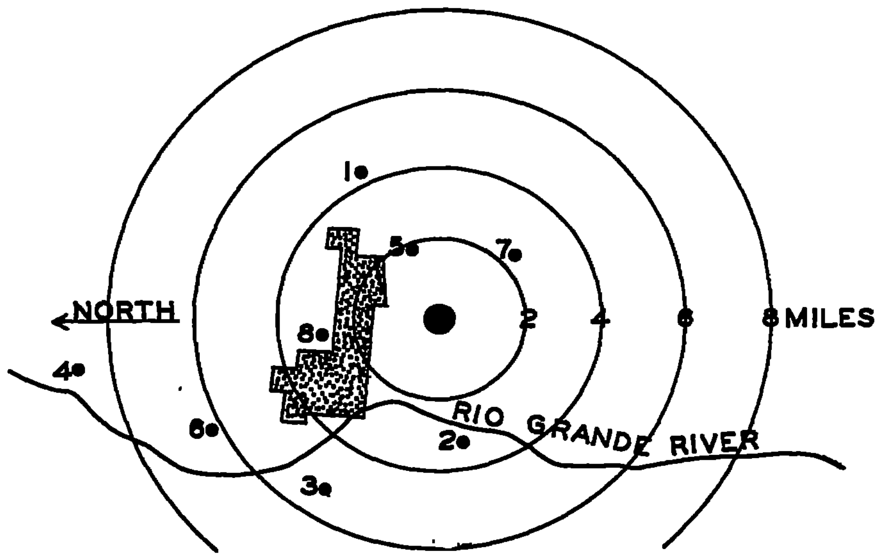

Figure 5.- Map showing location of instruments.

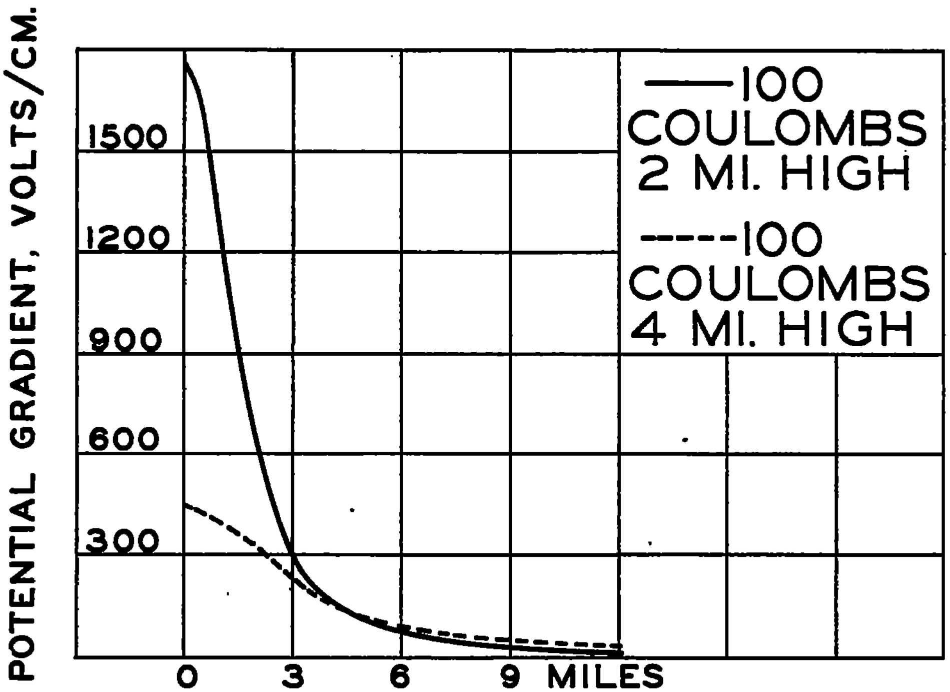

Figure 2.- Values of the potential gradient of two 100-coulomb charges.

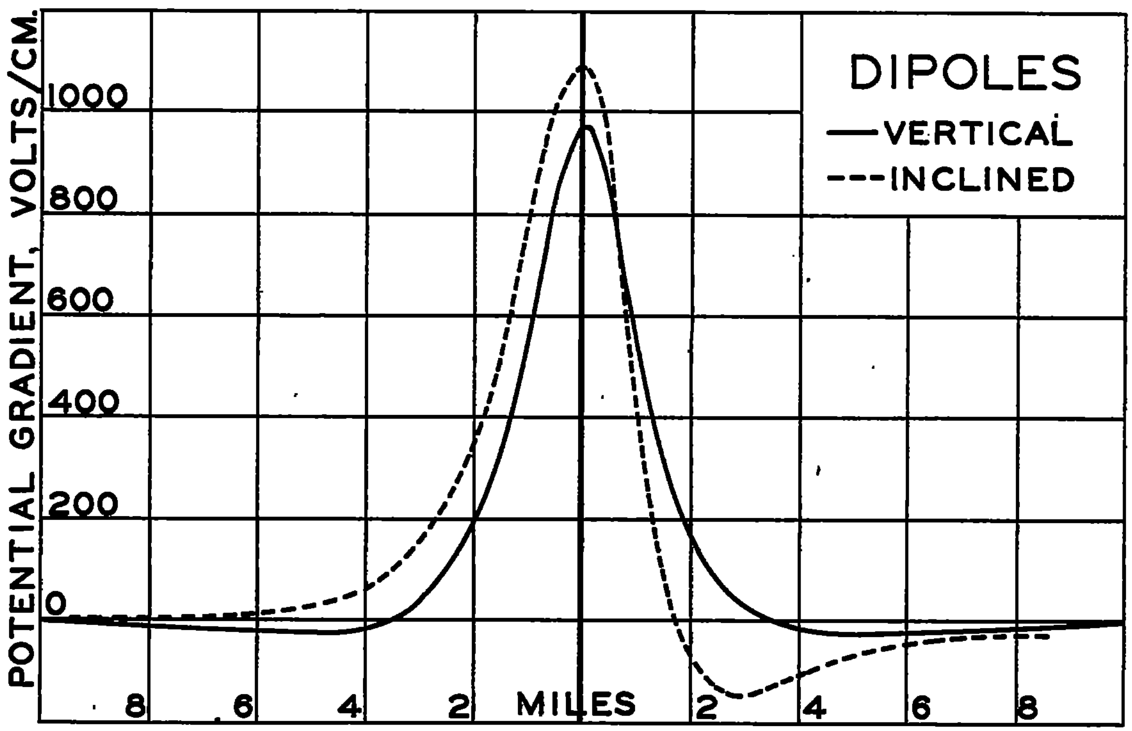

Figure 3.- The potential-gradient pattern for two dipoles.

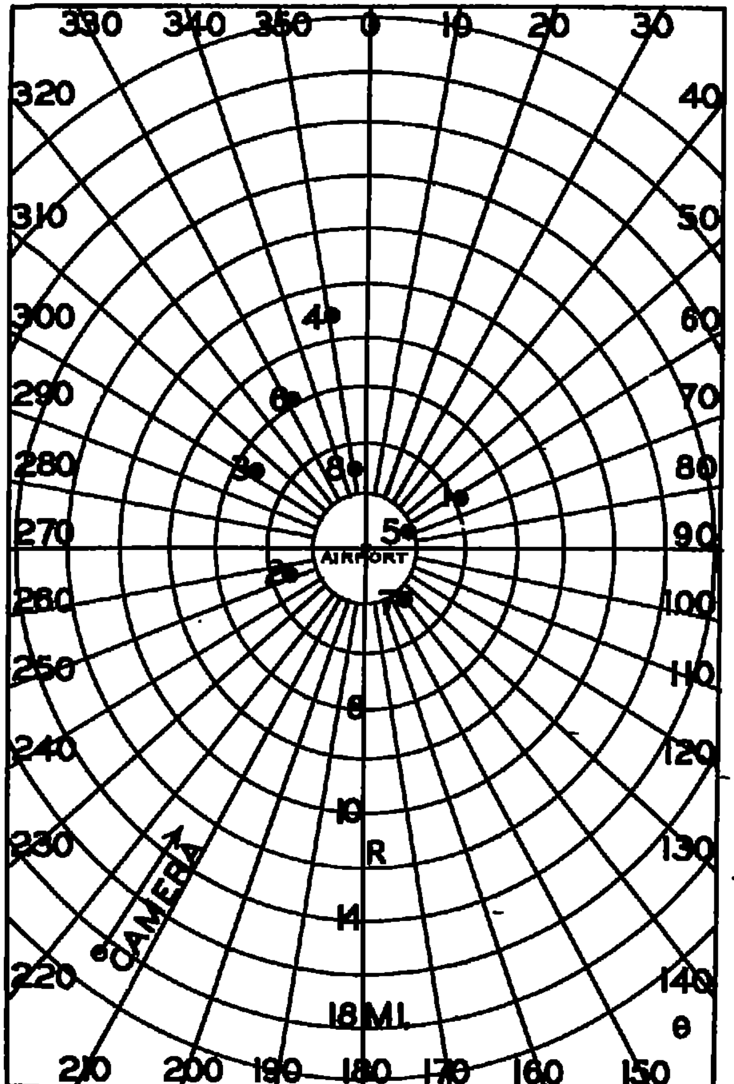

Figure 6.- Map of the instrument field and surrounding territory.

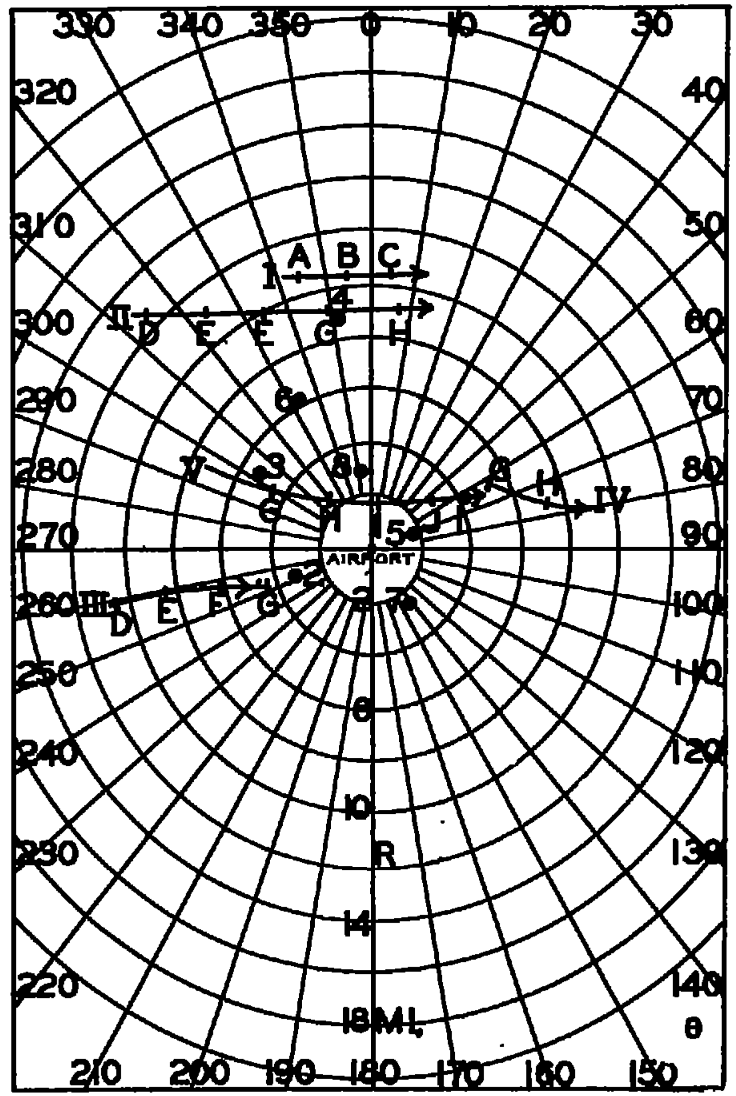

Figure 9.- Map of region during storm of August 20, 1939.

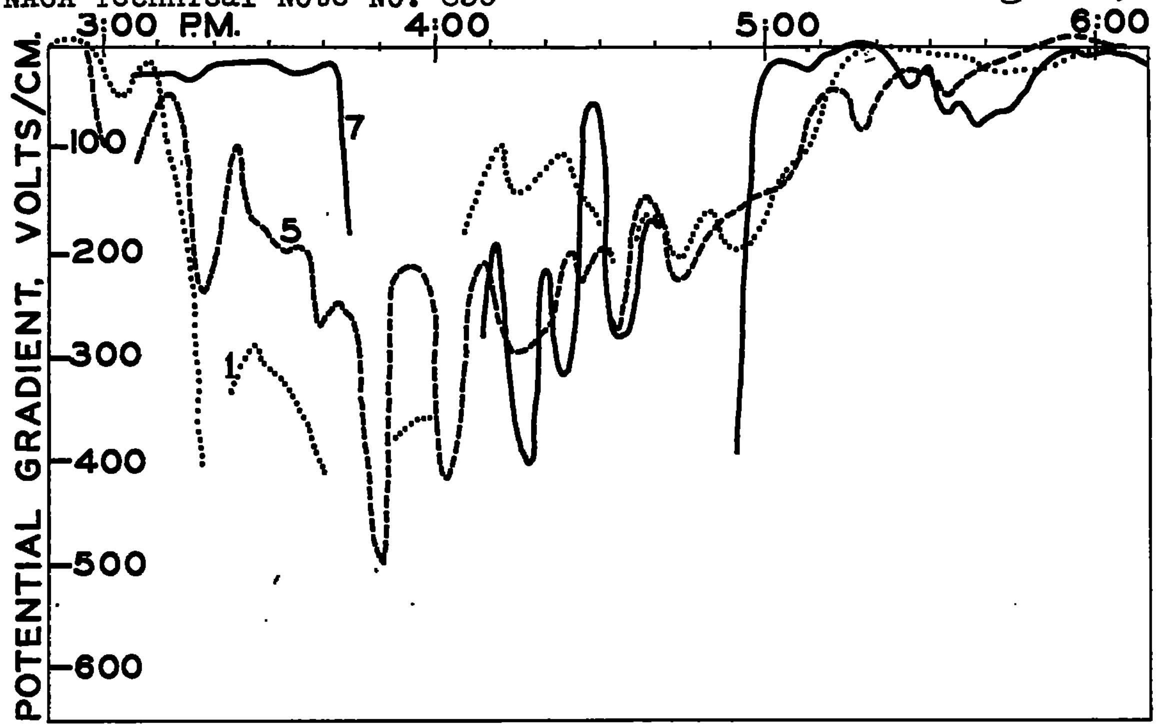

Figure 7a.- Data from storm of August 25, 1939. Instruments 1,5, and 7.

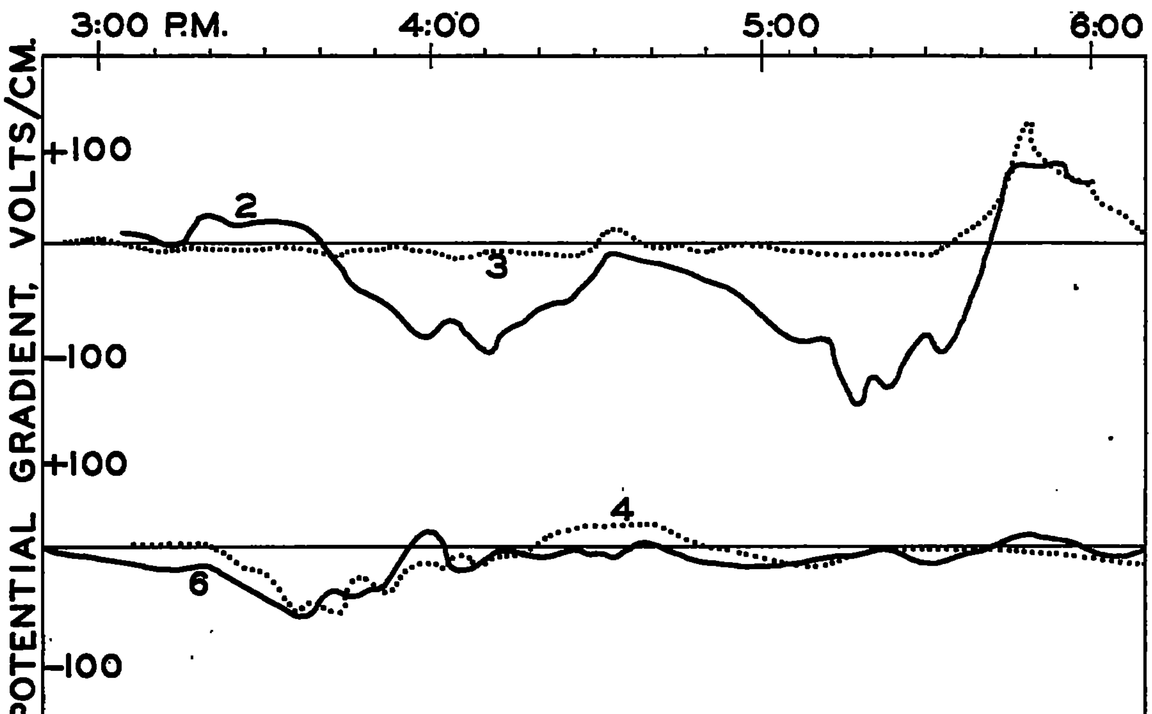

Figure 7b.- Data from storm of August 25, 1939. Instruments 2,3,4, and 6.

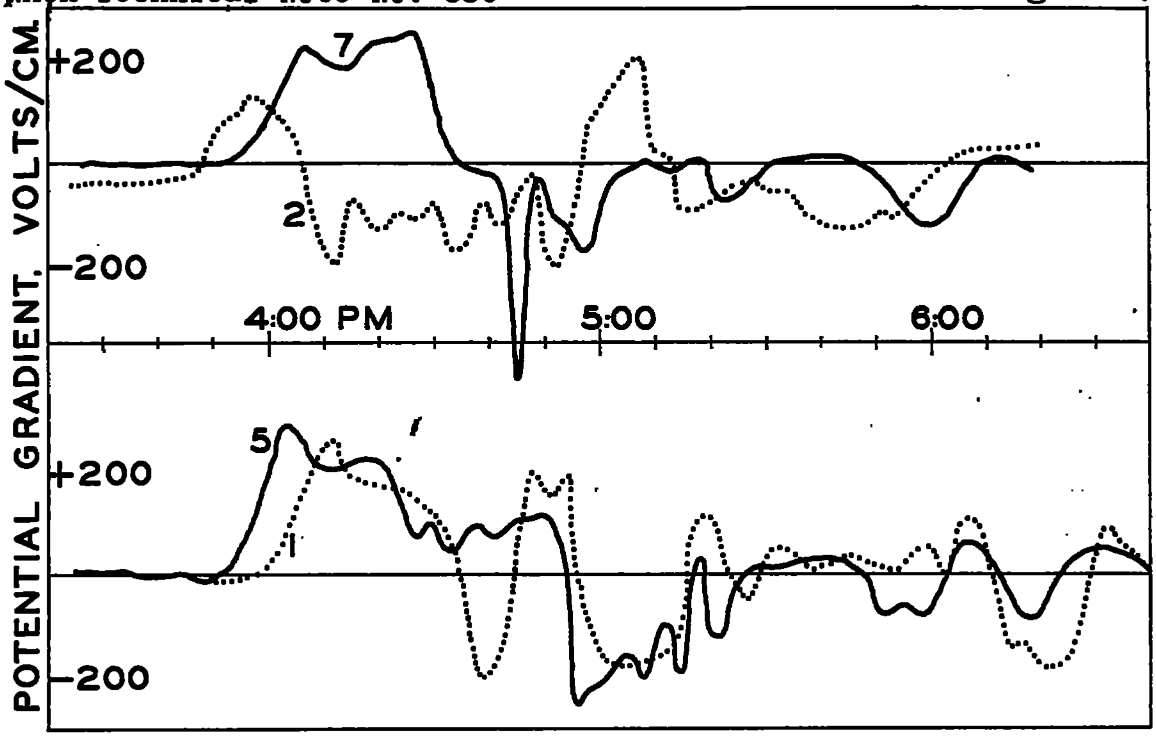

Figure 8a.- Data from storm of August 20, 1939. Instruments 1,2,5, and 7.

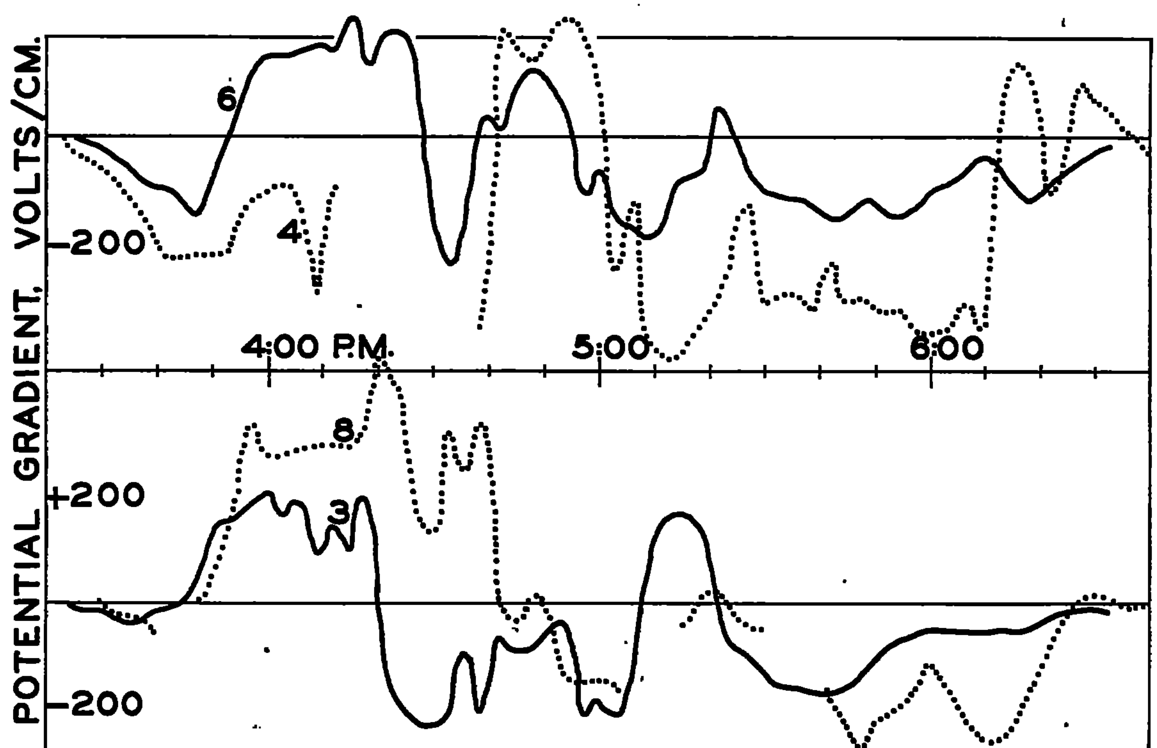

Figure 8b.- Data from storm of August 20, 1939. Instruments 3,4,6, and 8.

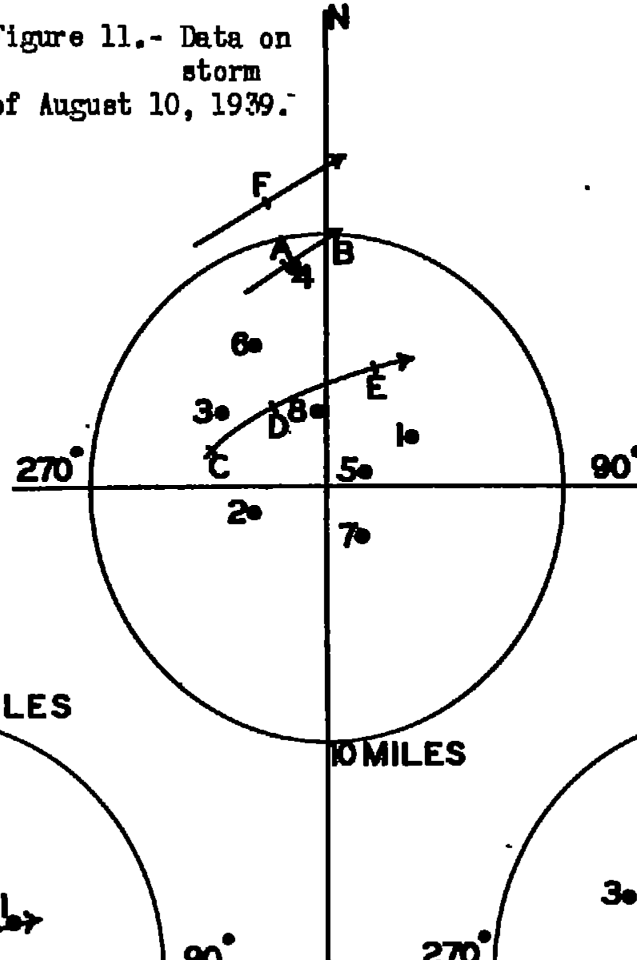

Figure 11.- Data on storm of August 10, 1939.

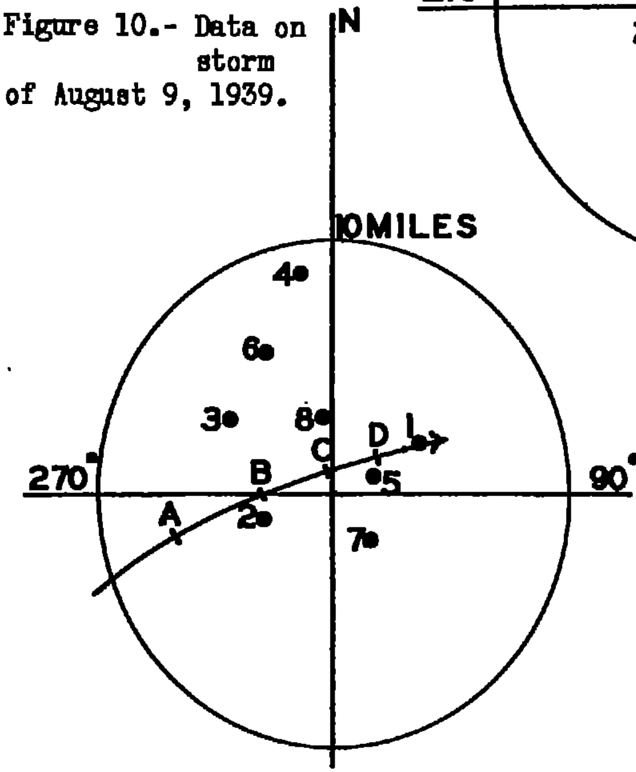

Figure 10.- Data on storm of August 9, 1939.

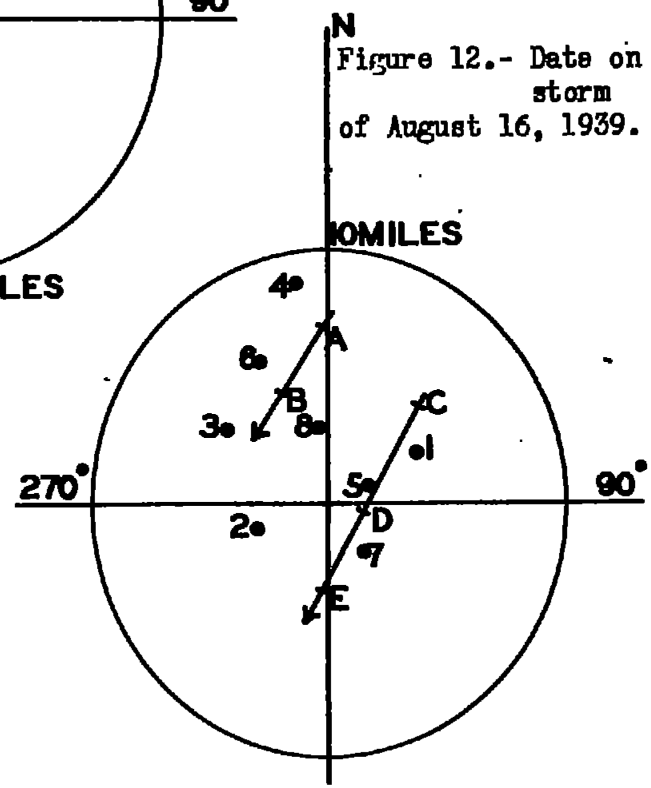

Figure 12.- Date on storm of August 16, 1939.